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(54) Improvements relating to chrominance selective filtering for use in colour video signal decoding

(57) A chrominance selective filter for filtering a sampled composite colour video signal to extract the composite chrominance component therefrom, includes a Fourier transform circuit (50) to convert a received sampled composite colour video signal from the time domain to the frequency domain and thereby provide a plurality of multi-dimensional frequency components. A transform domain filter (40) differentially changes the amplitudes of some of the frequency components relative to the others, without changing the phase information, and an inverse Fourier transform circuit (52) converts back from the frequency domain to the time domain. The transform domain filter changes the component amplitudes so as to select frequency components at least predominantly representing the composite chrominance component. This is done for a given component by locating the component which is in multi-dimensional frequency space at a mirror image position about a colour subcarrier, and setting the amplitude of the larger of the two components to that of the smaller component. The filter may operate in two dimensions (horizontal-vertical) or in three dimensions (horizontal-vertical-temporal).

The chrominance selective filter may be used in a PAL decoder, having a subtracter (14) which receives an input sampled composite colour video signal at its non-inverting input and the output of the filter at its inverting input, the filter also receiving the sampled composite colour video signal as an input. The filter output is the chrominance signal and the subtracter output is the luminance signal.

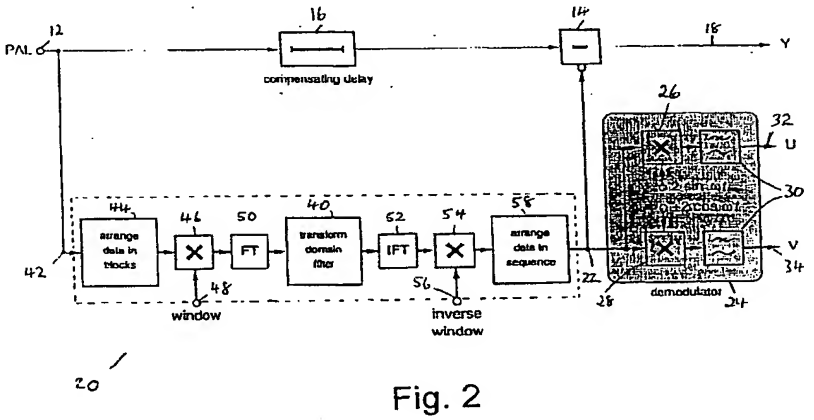

Fig. 2

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Description

Background of the Invention

[0001] This invention relates to chrominance selective filtering. The invention is particularly, though not exclusively, suitable for use in composite colour video signal decoding, especially PAL (Phase Alternate Line) decoders for use in television or at least video decoders.

[0002] The simplest form of chrominance filter for separating the chrominance component from a composite PAL signal is a band-pass filter. Various improved chrominance filters for PAL decoders have however been proposed. One example is a fixed multi-dimensional filter and is described in BBC Research Department Report No. 1988/11, Clarke, C.K.P., *Multi-dimensional filter design for chrominance-luminance separation,* November 1988. Such improved filters provide advantages but have material imperfections and when used in a PAL decoder still introduce undesired impairments. Some improved decoders make use of motion compensation. However, motion-compensated proposals in particular are prone to large errors if the motion estimation is not sufficiently accurate.

[0003] European Patent Application 0 690 632 and corresponding United States Patent 5,621,477 describe the use in a PAL decoder of a chrominance selective filter which includes a Hadamard transform. This operates only on a narrow band around the colour subcarrier frequency to select the composite colour component. It is stated that the Hadamard transform function can be replaced by a Fourier transform.

Summary of the Invention

[0004] The invention in its various aspects is defined in the independent claims below, to which reference should now be made. Advantageous features are set forth in the appendant claims.

[0005] A preferred embodiment of the invention is described in more detail below with reference to the drawings. This preferred embodiment takes the form of a chrominance selective filter for filtering a sampled composite colour video signal to extract the composite chrominance component therefrom, which includes a Fourier transform circuit to convert a received sampled composite colour video signal from the time domain to the frequency domain and thereby provide a plurality of multi-dimensional frequency components. A transform domain filter differentially changes the amplitudes of some of the frequency components relative to the others, without changing the phase information, and an inverse Fourier transform circuit converts back from the frequency domain to the time domain. The transform domain filter changes the component amplitudes so as to select frequency components at least predominantly representing the composite chrominance component. This is done for a given component by locating the component which is in multi-dimensional frequency space at a mirror image position about a colour subcarrier, and setting the amplitude of the larger of the two components to that of the smaller component. The filter may operate in two dimensions (horizontal-vertical) or in three dimensions (horizontal-vertical-temporal).

[0006] As an alternative to the Fourier transform, other transforms such as the Hadamard transform may be used. Alternatively, the signal may be separated into multi-dimensional frequency components in other ways. For example, 2-D or 3-D filters may be used, or one-dimensional filters may be cascaded to achieve the same effect. In any event, the signal is separated into a plurality of multi-dimensional frequency components before being filtered by the transform domain filter

[0007] The chrominance selective filter may be used in a PAL decoder, having a subtracter which receives an input sampled composite colour video signal at its non-inverting input and the output of the filter at its inverting input, the filter also receiving the sampled composite colour video signal as an input. The filter output is the chrominance signal and the subtracter output is the luminance signal.

Brief Description of the Drawings

[0008] The invention will now be described in more detail, by way of example, with reference to the drawings, in which:

Figure 1 is a block circuit diagram showing a known complementary PAL decoder;

Figure 2 is a block circuit diagram of a PAL decoder using a Fourier domain chrominance filter embodying the present invention;

Figure 3 is a diagram showing the horizontal-vertical spectrum of a PAL signal, illustrating the operation of the decoder of Figure 2 with a 2-dimensional (2-D) filter;

Figure 4 is a block circuit diagram of a circuit used in the decoder of Figure 2;

Figure 5 is a diagram showing the vertical-temporal spectrum of a PAL signal, illustrating the operation of the decoder of Figure 2 with a 3-dimensional (3-D) filter; and

Figure 6 is a diagram showing the vertical-temporal spectrum of a PAL signal with interval displacement of fields prior to the Fourier transform.

Detailed Description of the Preferred Embodiment

[0009] Much of the archive material held by broadcasters and others is still stored in PAL composite format. Before this material can be broadcast on a digital network the PAL signals must be decoded. This inevitably has introduced some residual cross-effects, in particular dot patterns and false colours. The existence of these cross-effects means that a higher bit rate is re-

quired for accurate digital transmission.

[0010] One known PAL decoder based on the analogue PAL decoder described in United Kingdom Patent Specification 1,482,079 is illustrated in Figure 1 of the accompanying drawings. The decoder 100 shown in Figure 1 has an input 112 for receiving a composite colour video signal in the form of a PAL signal to which is connected a chrominance subcarrier filter 120. The filter 120 is a frequency selective filter which selects the frequencies which contain predominantly chrominance rather than luminance information. A subtracter 114 is connected to receive the output of the filter 120 at its inverting input, and the PAL input signal, after passing through a compensating delay 116 which compensates for the delay in the filter 120, at its non-inverting input. The output 118 of the subtracter 116 constitutes the luminance signal and the output 122 of the filter 120 constitutes the decoded composite chrominance signal. This latter signal is then demodulated in a demodulator 124 in one of a number of possible known ways. As shown, the decoded composite chrominance signal is applied to two multipliers 126, 128 which receive signals at colour subcarrier frequency. The two signals are in phase quadrature, with one multiplier receiving an in-phase signal and the other multiplier receiving a quadrature-phase signal, the phase of which is inverted on alternate lines in accordance with the PAL system. The multiplier outputs are then low-pass filtered by low-pass filters 130 to provide the U and V output signals 132 and 134.

[0011] In this "complementary" decoder shown in Figure 1, the PAL signal is filtered in the filter 120 with the intention of isolating the modulated chrominance. This is then subtracted from the PAL signal in the subtracter 114 to give "clean" luminance, and demodulated to give "clean" colour components.

[0012] In its simplest form, the chrominance subcarrier filter 120 shown in Figure 1 is a horizontal band-pass filter centred on subcarrier frequency f_{SC}. Better results can be obtained by using a 2 dimensional (horizontal-vertical) filter or a 3 dimensional (horizontal-vertical-temporal) filter, as f_{SC} has vertical components at 72 c/aph and 216 c/aph and temporal components at 6.25 Hz and 18.75 Hz.

[0013] Figure 2 illustrates an embodiment of the present invention in which the chrominance selective filter 120 of Figure 1 is replaced by a chrominance selective filter 20 embodying the present invention. Except for the chrominance filter, the circuit of Figure 2 is the same as Figure 1.

[0014] Thus the PAL decoder 10 of Figure 2 has an input 12 for receiving a composite PAL signal to which is connected a chrominance subcarrier filter 20, the construction of which is described below. A subtracter 14 is connected to receive the output of the filter 20 at its inverting input, and the PAL input signal, after passing through a compensating delay 16 which compensates for the delay in the filter 20, at its non-inverting input. The output 18 of the subtracter 16 constitutes the luminance signal and the output 22 of the filter 20 constitutes the decoded composite chrominance signal. As with Figure 1, this latter signal is then demodulated in a demodulator 24 in one of a number of possible known ways. As shown, the decoded composite chrominance signal is applied to two multipliers 26, 28 which receive signals at colour subcarrier frequency. The two signals are in phase quadrature, with one multiplier receiving an in-phase signal and the other multiplier receiving a quadrature-phase signal, the phase of which is inverted on alternate lines in accordance with the PAL system. The multiplier outputs are then low-pass filtered by low-pass filters 30 to provide the U and V output signals 32 and 34.

[0015] The filter 20 embodying the invention and shown in Figure 2 filters the PAL signal in the Fourier transform domain. The filtering is effected by a Fourier transform domain filter circuit 40, as described below. The filter 20 operates with digital signals. The filter 20 has an input 42 connected to the input 12 of the PAL decoder 10 to receive a digital composite chrominance signal. To the input 42 is connected a circuit 44 which arranges the incoming data into blocks. A multiplier 46 is connected to the output of the data arranging circuit 44 and receives a window signal at an input 48. The multiplier is arranged to reduce the effect of black edges. The output of the multiplier 46 is then applied to a Fourier transform circuit 50, conveniently implemented as a fast Fourier transform or FFT circuit. The transformed signal from the Fourier transform circuit 50 is then applied to the transform domain filter circuit 40. The operation of the transform domain filter circuit 40 is described below.

[0016] The output of the transform domain filter circuit 40 is then reverse processed and is applied to an inverse Fourier transform circuit 52 also conveniently implemented as an FFT, a second multiplier 54 receiving a window signal at an input 56, and a data arranging circuit 58 which rearranges the data from blocks back into a sequence corresponding to that received at the input 42. The (forward) Fourier transform and the inverse Fourier transform could, in principle, be rearranged. The output 22 of the data arranging circuit 58 constitutes the output of the filter 20.

[0017] Unlike the circuit of Figure 1, the circuit of Figure 2 requires the PAL signal to be in digital form or at least to be sampled. A good choice of sampling frequency is four times the colour subcarrier frequency f_{SC}, viz. 4 f_{SC}.

[0018] In the circuit of Figure 2, the incoming PAL signal is firstly rearranged into 2 or 3 dimensional blocks in the data arranging circuit 44. The blocks may have some degree of overlap if desired. The samples are then multiplied in the multiplier 46 by a window function received at input 48, to reduce the effects of block edges, before being transformed into "frequency space" by a discrete Fourier transform applied to each block by the Fourier transform circuit 50. A Fourier transform is an example

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of a time domain to frequency domain transform. The transform domain filter 40 then modifies some or all of the samples in a block, before it is converted back to "signal space" by an inverse Fourier transform in the inverse Fourier transform circuit 52. After multiplying by the inverse of the window function in the multiplier 54, the samples are put back into the correct time order in the data arranging circuit 58. If the blocks have overlap, then some form of averaging or "cross-fading" may be used to combine samples from adjacent blocks.

[0019] As an alternative to the Fourier transform, other transforms such as the Hadamard transform may be used. Alternatively, the signal may be separated in multi-dimensional frequency components in other ways. For example, 2-D or 3-D filters may be used, or one-dimensional filters may be cascaded to achieve the same effect. In any event, the signal is separated into a plurality of multi-dimensional frequency components before being filtered by the transform domain filter 40.

[0020] Where the incoming PAL signal is interlaced, as will be the case with normal broadcast television signals for example, lines of zero samples are inserted, so as to make an orthogonal sampling structure, before temporal Fourier transforms can be applied. This doubles the amount of data to be processed, but the spectral repeat at (288 c/aph [cycles per active picture height], 25 Hz) enables some efficiency improvement by only processing half of the transform domain data.

[0021] Alternatively, prior to taking the Fourier transform successive fields can be vertically displaced, the displacement increasing or decreasing at one picture line per field interval. This displacement may be reset to zero at the start of each block. An opposite displacement is applied after the inverse Fourier transform.

[0022] In effect this means that we are not using an orthogonal structure for the Fourier Transform. The effect of this displacement in frequency space is to offset the temporal frequency by an amount proportional to the vertical frequency. The U subcarrier at (+72 c/aph, +18¾ Hz) is moved to (+72 c/aph, +12½ Hz) and the V subcarrier at (-72 c'aph, -18¾ Hz) is moved to (-72 c/aph, -12½ Hz). This is shown in Figure 6 which is equivalent to Figure 5.

[0023] Although the displacement changes temporal frequencies, all the symmetries still hold and so the method still works, as illustrated in the attached figure. The overhead of inserting lines of zero before forming the Fourier transform is removed, a significant saving in hardware costs.

[0024] Using Fourier transforms as described above has some disadvantages. The circuit is relatively complex, and the use of blocks may produce visible artefacts. However, we have appreciated that it offers one great advantage over the conventional circuit of Figure 1, namely that the filter characteristic can easily be varied, in particular according to the spectrum of the incoming signal.

[0025] Figure 3 is a diagram illustrating the horizontal-vertical spectrum of a PAL signal, more particularly it represents the 2-D Fourier transform of one field of a $4f_{sc}$ sampled PAL signal. The dotted grid lines represent the boundaries between Fourier transform samples, assuming a block size of 16 x 16 samples. The following specific points may be seen on the Figure:

zero frequency 0 is at the centre,
the U colour subcarrier is at: ($+f_{SC}$, +72 c/aph) and ($-f_{SC}$, -72 c/aph) and
the V subcarrier is 144 c/aph away, at:
($+f_{SC}$, -72 c/aph) and ($-f_{SC}$, +72 c/aph).

[0026] After passing through a 2-D FFT circuit, the separate frequency components of the signal will be available and may be plotted on a Figure like Figure 3. Consider an arbitrary frequency shown at X in Figure 3. This Fourier sample could contain some combination of luminance, modulated U and modulated V, although each of these would generally have a different baseband frequency. If the sample contained only modulated U, then the same amount of modulated U should be present in the sample X', which is the "mirror" of X about the U carrier ($+f_{SC}$, +72 c/aph). Similarly, if the sample contained only modulated V, then the same amount of modulated V should be present in the sample X', which is also the mirror of X about the V carrier ($+f_{SC}$, -72 c/aph). It will be appreciated that the Fourier transform is periodic, and this diagram shows just one "cycle". If you "go off the edge" then you reappear at the opposite side. Note that X and X' are also mirror pairs about the two other carriers ($-f_{SC}$, +72 c/aph) and (f_{SC}, -72 c/aph).

[0027] In practice, the modulated U and V signals are not completely symmetric about their subcarriers, as the composite PAL signal is usually low-pass filtered with a cut frequency of about 5.5 MHz.

[0028] We have appreciated that the Fourier transform domain signal can be filtered by differentially changing the amplitudes of some of the frequency components. The phases should however not be altered.

[0029] We have furthermore appreciated that the symmetries described in relation to Figure 3 make it possible to construct a chrominance filter in the following manner. In this preferred chrominance filter, the magnitude of each Fourier sample is compared with that of its "mirror" sample. The magnitude of both of these samples are then set to the smaller of the pair. In this way components which at least predominantly represent chrominance are selected. This simple method has been found to provide remarkably good results for a PAL decoder with no temporal processing.

[0030] As described the mirroring has taken place about the U subcarrier. However, due to the cyclic nature of the Fourier transform, as noted above, each sample has just one mirror, regardless of which subcarrier is chosen. Accordingly the same result is achieved by mirroring about the V subcarrier.

[0031] Figure 4 shows in diagrammatic form a circuit

70 for determining the smaller of the two subcarriers and replacing the larger amplitude of the two by the smaller amplitude, in accordance with the method illustrated in Figure 3. The phase is not however changed. A component frequency is received at an input 72 and a circuit 74 locates the component which is at the mirror image position about the subcarriers. The values of the amplitudes of these two components is compared in a circuit 76 which determines which of the two is the smaller and the ratio of the amplitudes of the two components. It provides two outputs to two respective multipliers 78, 80, associated with the two components respectively. The output to the one of the multipliers associated with the smaller of the two components is a unity multiplying factor. The output to the other of the two multipliers 78, 80, the one associated with the component of larger amplitude, conveys a multiplying factor less than unity dependent upon the ratio of amplitudes determined in circuit 76. This has the effect of reducing the amplitude of the larger component to that of the smaller component. The phases of the signals are unaffected. In practice the circuit 70, as with other circuits described, may be implemented in software, in which case the figure should be regarded as a flowchart rather than a hardware block diagram.

[0032] As an alternative to the arrangement of Figure 4, if the comparison between the two components indicates that the ratio of one to the other falls below a predetermined threshold then both are discarded. This is achieved by setting them to zero. The threshold used is partially picture dependent but one example is to discard both if one component has an amplitude of less than 40% of the other. Other values may be used but it is preferable for a hardware decoder to have a single fixed value.

[0033] There are two areas where this simple decoder may fail. Firstly, low pass filtering of the PAL signal to 5.5 MHz creates an asymmetric modulated chrominance spectrum. Frequencies that have been attenuated are no longer the same amplitude as their "mirrors". Consequently these will be decoded as luminance. This may produce visible patterning, and the decoded chrominance bandwidth is restricted to 1.1 MHz. Secondly, if the baseband chrominance contains both U and V at a vertical frequency of ±72 c/aph, then after modulation the -72 c/aph U has the same frequency as the +72 c/aph V, and vice versa. This can produce an asymmetry in the magnitudes of the Fourier components, so this chrominance also appears as cross luminance. The second of these two effects can be quite visible on vertical colour transitions (e.g. the horizontal edges in a colour patches test pattern) unless they are bandwidth limited.

[0034] Figure 5 shows a vertical-temporal slice through the 3-D spectrum of a PAL signal. Note that the slice is at a horizontal frequency of $+f_{SC}$; a slice at $-f_{SC}$ would look similar but the locations of the U and V subcarriers would be swapped.

[0035] Clearly, each U and V subcarrier in Figure 5 is its own reflection in any of the subcarriers. There is another set of frequencies with the property, 25Hz away from the subcarriers, for example (+72 c/aph, -6¼ Hz). Energy at these frequencies will be demodulated as colour with a 25 Hz component - this might be a genuine signal, but is more likely to be cross-colour. A variation of the decoder design is to force these samples to zero, so they will always be interpreted as luminance.

[0036] As in Figure 3, X is an arbitrary frequency, and X' is its mirror about the U carrier at (+72 c/aph, +18.75 Hz). Because the PAL signal is interlaced, every Fourier sample is repeated at a distance of (±288 c/aph, ±25 Hz) so X and X' each appear twice, as do the U and V subcarriers. As before, X' is also the mirror of X about all the other carriers. To keep the diagram simple, half of the arrows that could be drawn have been omitted, and thus only half are shown.

[0037] These symmetries enable the 2-D transform domain filter described above with reference to Figure 3 to be extended to 3 dimensions. This completely cures the problem the 2-D filter has with chrominance at frequencies around ±72 c/aph, because the U and V carriers have different temporal frequencies, except when there is a temporal transient such as a shot change. When this happens the signals are spread across all temporal frequencies, and the 3-D filter reduces to a 2-D filter with the same horizontal and vertical block size.

[0038] The preferred block size to be set by the data arranging circuit 44 of Figure 2 will now be considered. One option is to set the block size by requiring a Fourier sample to be centred on a colour subcarrier. The PAL signal is sampled at 4 f_{SC}, so the minimum horizontal block size is 4. For a 2-D filter the vertical sampling frequency is 288 c/aph, and subcarrier is at 72 c/aph, so the block size is 4 field lines. For a 3-D filter the vertical sampling frequency is 576 c/aph, so the block size is 8 picture lines. The temporal block size, for a 3-D filter, is 8 fields, as the temporal sampling frequency is 50 Hz, and subcarrier is at 6.25 Hz (and 18.75 Hz).

[0039] We have found that when using this block size each Fourier sample contains a wide range of frequencies (particularly when the effects of "leakage" are considered) and it is unlikely that any Fourier sample would contain only luminance or only chrominance.

[0040] The method also works if the boundary between blocks is centred on a subcarrier instead since this arrangement is also symmetric. In this case we can have a 3-D version with blocks as small as 4 samples x 2 field lines x 2 fields with the fields displaced as described above.

[0041] The upper limit to the block size is set by the picture dimensions (a 4f_{SC} sampled PAL frame has 576 lines of 945 samples). However, the decoded picture quality degrades as the blocks get larger than about 64 samples or picture lines. This may be because large blocks cover a larger area of picture, so are more likely to encompass different picture material with a wide

range of frequencies. We have found that a block size of 16 samples x 32 picture lines x 8 fields provides good results. However, a range of block sizes between 8 samples x 16 picture lines x 4 fields to 32 samples x 64 picture lines x 16 fields may be considered.

[0042] For good quality results it is desirable to use some sort of window function in filters of the kind illustrated by the multipliers 46, 54 in Figure 2. A raised cosine window with completely overlapping blocks may be employed. This has the advantage that no inverse windowing is required, as overlapping blocks are simply added together. Windowing in the temporal dimension, using non-overlapping blocks, may give a useful saving in processing and storage, at the expense of a small reduction in decoded picture quality. Other window functions could be used, and the block overlap need not be 100%.

[0043] One example of the invention has been described. Many modifications may be made to the system illustrated and the invention may be implemented in many ways different from that described.

Claims

1. A method of filtering a sampled composite colour video signal to extract the composite chrominance component therefrom, the method comprising the steps of:

   separating the signal into a plurality of multi-dimensional frequency components;
   differentially changing the amplitudes of some of the frequency components to select frequency components at least predominantly representing the composite chrominance component; and
   combining the resultant frequency components to provide a sampled output signal.

2. A method according to claim 1, in which the changing step comprises:

   comparing components which are located at mirror images about the colour subcarrier in frequency space;
   setting the amplitude of the larger of the compared components to that of the smaller.

3. A method according to claim 2, in which the frequency space is a three dimensional frequency space (horizontal-vertical-temporal).

4. A method according to claim 2, in which the frequency space is a two dimensional frequency space.

5. A method according to claim 1 in which the changing step comprises:

   comparing components which are located at mirror images about the colour subcarrier in frequency space;
   determining the ratio of amplitudes of the components;
   setting both components substantially to zero if one is less than a predetermined proportion of the other.

6. A method according to claim 1, in which the separating step comprises subjecting the sampled composite colour video signal to a time domain to frequency domain transformation, and the combining step comprises subjecting the resultant frequency components to a frequency domain to time domain transformation.

7. A method according to claim 6, in which the time domain to frequency domain and frequency domain to time domain transformations comprise a Fourier transform and an inverse Fourier transform.

8. A method according to claim 6 or 7, further comprising the steps of:

   prior to the time domain to frequency domain transformation, arranging the samples of the sampled composite colour video signals into blocks; and
   after the frequency domain to time domain transformation, re-arranging the samples back into sequential form.

9. ~~A method according to claim 8, in which the blocks are three~~ dimensional blocks of a size between 8 samples x 16 picture lines x 4 fields and 32 samples x 64 picture lines x 16 fields.

10. A method according to claim 8 or 9, in which the blocks overlap.

11. A method according to claim 8, 9 or 10, further comprising between the arranging step and the time domain to frequency domain transformation, applying a windowing function to block edges.

12. A method according to claim 11, in which the windowing function is a raised cosine function.

13. A method according to any of claims 1 to 12, in which the composite colour video signal is a PAL signal.

14. A method according to claim 13, in which the composite colour video signal is sampled at four times the colour subcarrier frequency.

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15. A method according to any preceding claim, in which the composite colour video signal is an interlaced signal, the method further comprising the step of inserting lines of zero samples so as to make an orthogonal sampling structure prior to the time domain to frequency domain transformation.

16. Apparatus for filtering a sampled composite colour video signal to extract the composite chrominance component therefrom, comprising:

means for separating the signal into a plurality of multi-dimensional frequency components;
means for differentially changing the amplitudes of some of the frequency components to select frequency components at least predominantly representing the composite chrominance component; and
means for combining the resultant frequency components to provide a sampled output signal.

17. A composite colour video signal decoder, comprising:

an input for receiving a sampled composite colour video signal;
a subtracter having its non-inverting input coupled to the input; and
a chrominance filter coupled to the input and having its output coupled to the inverting input of the subtracter;

wherein the chrominace filter comprises apparatus in accordance with claim 16.

18. A method of filtering a sampled composite colour video signal to extract the composite chrominance component therefrom, substantially as herein described with reference to Figure 2 *et seq.* of the drawings.

19. Apparatus for filtering a sampled composite colour video signal to extract the composite chrominance component therefrom, substantially as herein described with reference to Figure 2 *et seq.* of the drawings.

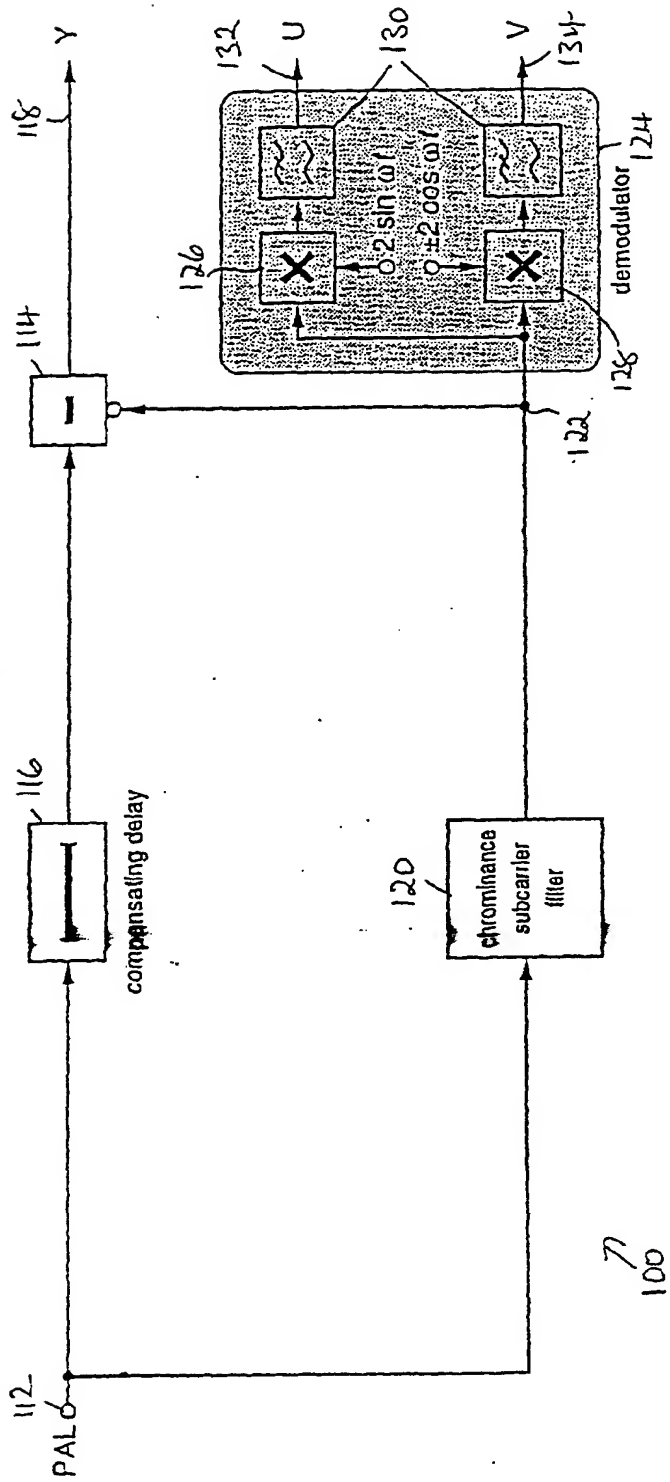

Fig. 1 PRIOR ART

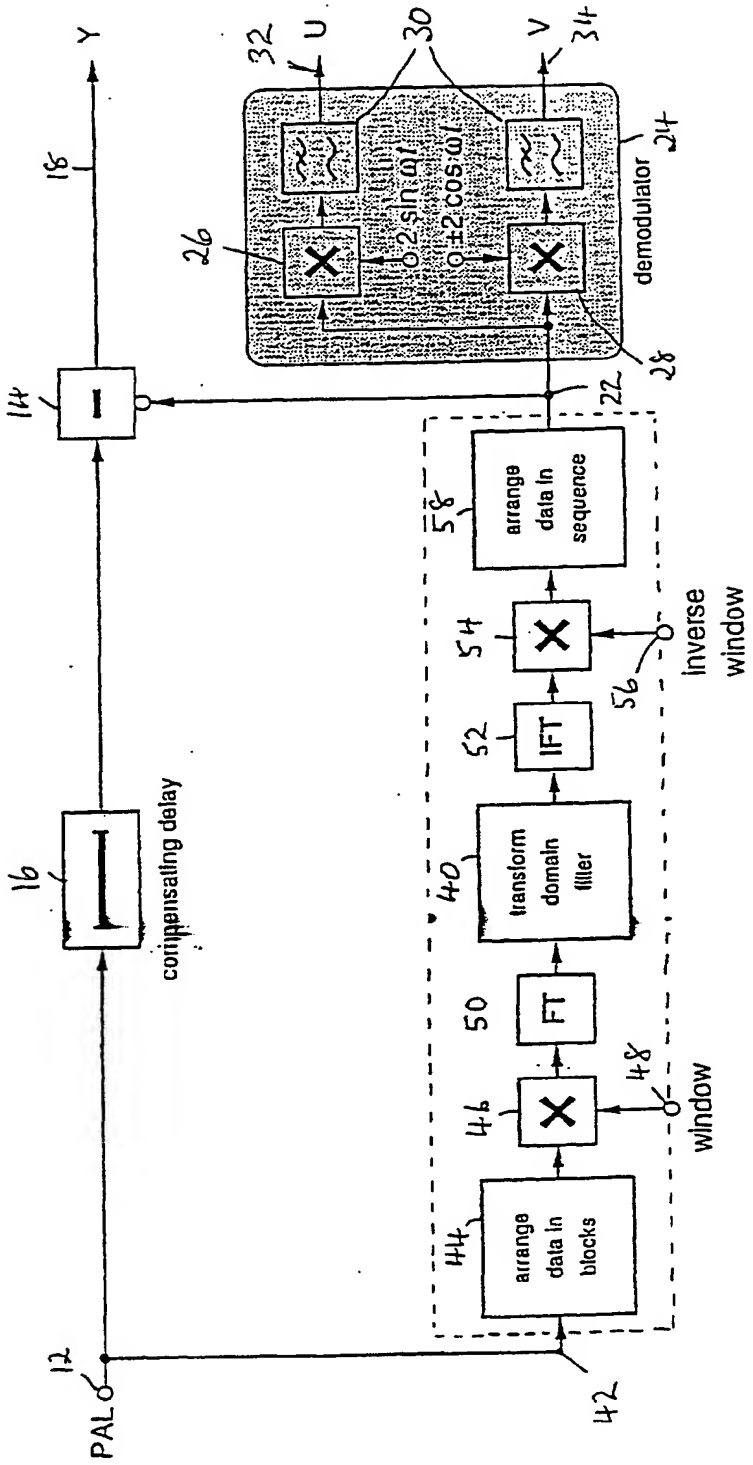

Fig. 2

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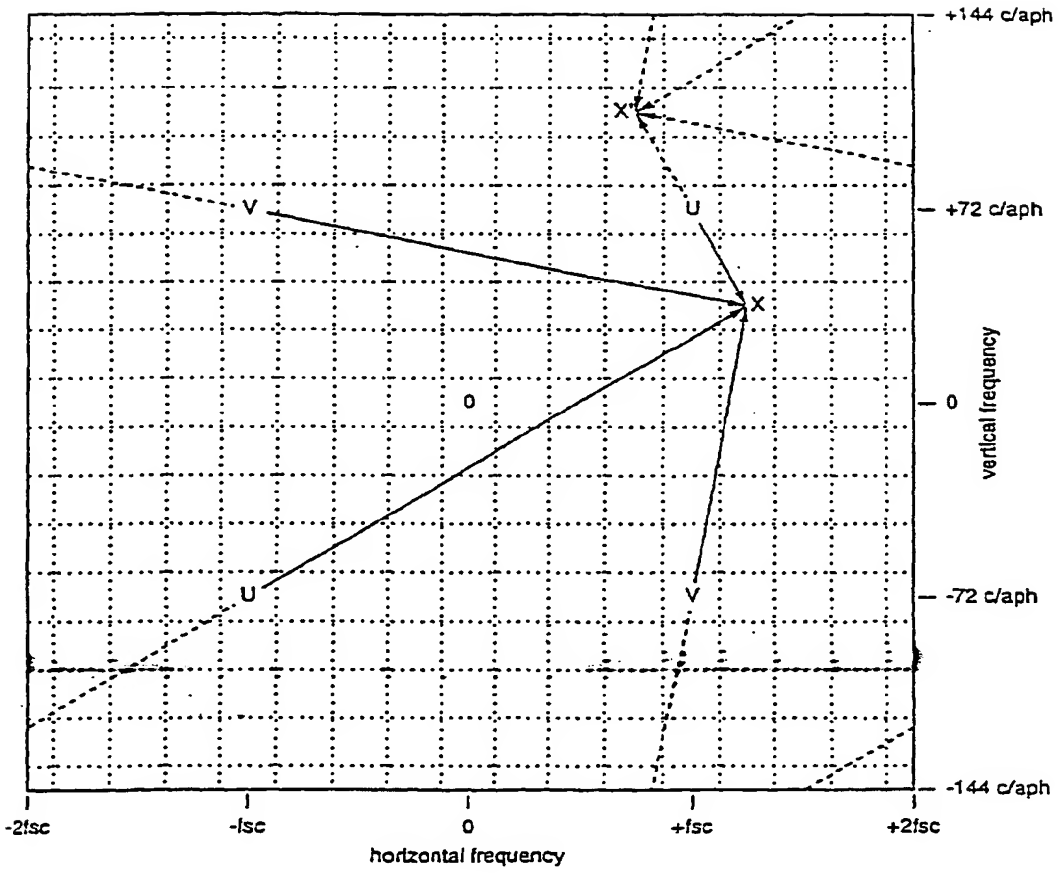
+144 c/aph
+72 c/aph
0
-72 c/aph
-144 c/aph
vertical frequency
X'
V
U
X
0
U
V
-2fsc
-fsc
0
+fsc
+2fsc
horizontal frequency

Fig. 3

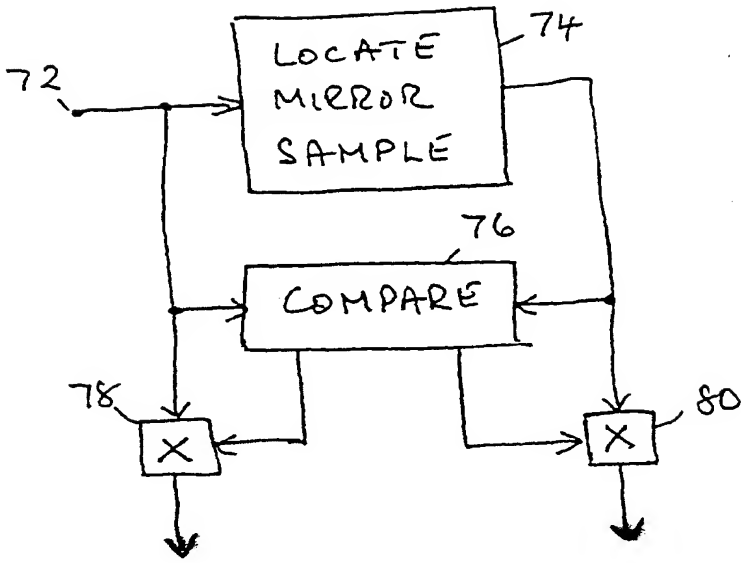

Fig. 4

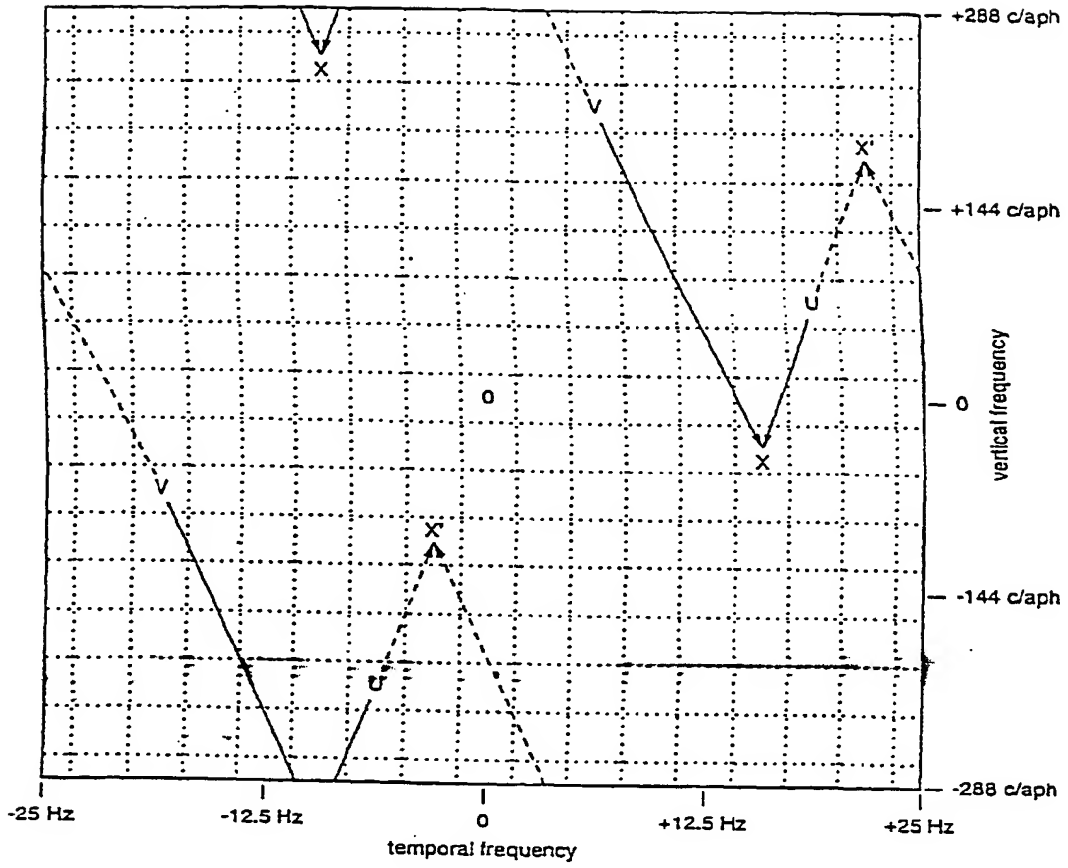

Fig. 5

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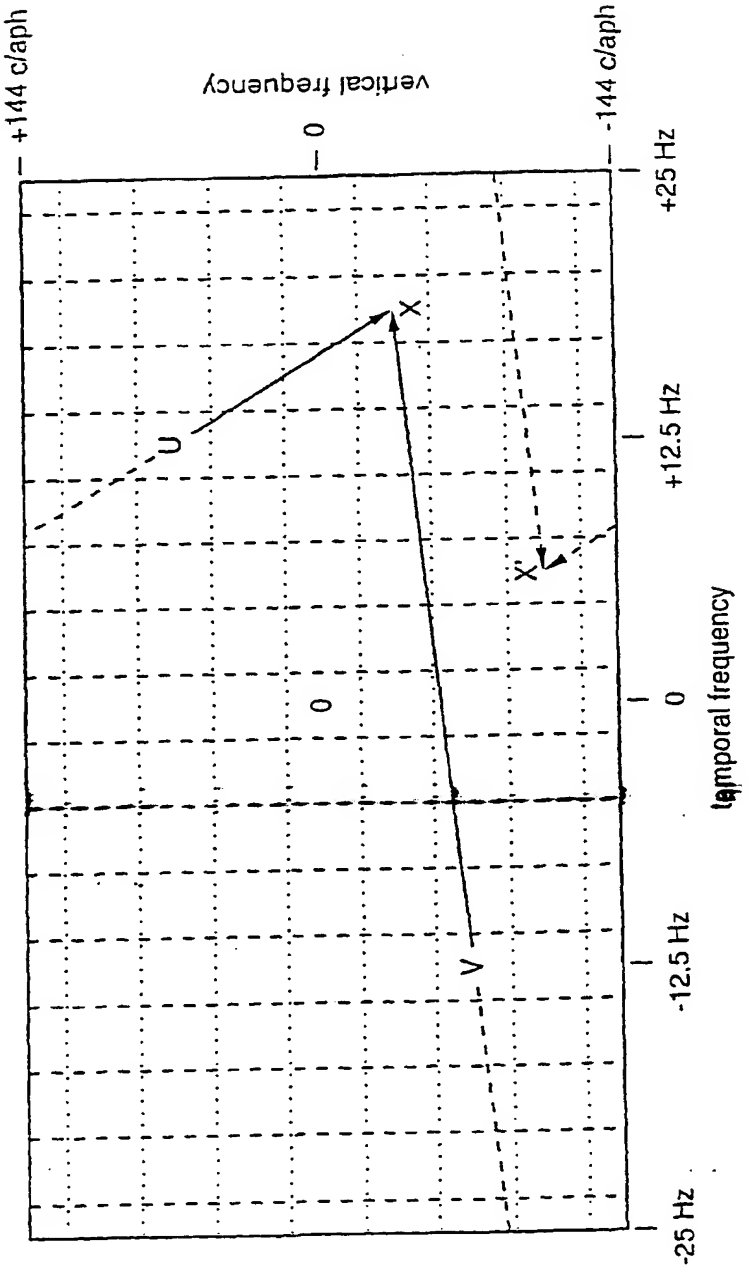
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vertical frequency
0
-144 c/aph
+25 Hz
+12.5 Hz
0
-12.5 Hz
-25 Hz
temporal frequency
U
X
X'
V
0

Figure 6